

Tidal Channel Dynamics and Muddy Substrates: A Comparison Between a Wave Dominated and a Tidal Dominated System

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OBJECTIVES

To determine the feedbacks between waves, tidal fluxes and tidal channels in muddy coastlines

To link the geotechnical properties of sediment substrates to the spatial and hydrodynamic characteristics of tidal channels

To develop new morphological indicators of tidal flat morphodynamics that can be easily derived from remote sensing images. To link these indicators to mechanical properties of tidal flat substrates

To compare the results of the MURI project “Mechanisms of Fluid Mud Interactions under Waves” to wave measurements at the shoreline.

To integrate high resolution hydrodynamic measurements within ongoing research activities at the Willapa Bay “Tidal Flats” DRI location

APPROACH

Field component

The field campaign in along the Louisiana coastline and in Willapa Bay was divided in four components:

2.1 INTERPLAY BETWEEN WAVES AND TIDAL CHANNEL HYDRODYNAMICS ALONG THE LOUISIANA COAST

We focused our research on Little Constance Bayou, a creek in the Rockefeller State Wildlife Refuge, Louisiana. Our goal was to characterize the fluxes of sediments from the shelf to the marshes. We deployed a Nortek ADCP at the mouth of the creek to measure tidal elevation, water velocity, and concentration of suspended sediment in time. A Sontek ADV was deployed in the bay in front of the channel mouth to record wave characteristics during the studied period.

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2.2 TIDAL CHANNEL HYDRODYNAMICS IN WILLAPA BAY MUDEFLATS

The goal of this task was to determine the feedbacks among tidal circulation, wind waves, and channels in a muddy tidal flat. To address this scientific question we deployed five Nortek current profilers (ADCPs) and two RBR wave sensors in the Willapa Bay mudflats, WA (Fig. 1). The ADCPs measured wave characteristics, water velocity, tidal elevation, and suspended sediment concentration every 30 min from February 20, 2010 to April 23, 2010. This second deployment was complementary to the first deployment in July 2009, in which we only measured tidal fluxes in one channel for two weeks.

2.3 WAVE CHARACTERISTICS IN MUDEFLATS

All five ADCPs measured wind waves at 2Hz every 30 min. To expand the spatial resolution of the wave measurements we deployed two high resolution RBR pressure transducers (see Fig. 1). We were fortunate to capture extreme weather conditions on March 29, 2010 with wind speed at 40 knots (strong gale) and gusts at 50 knots.

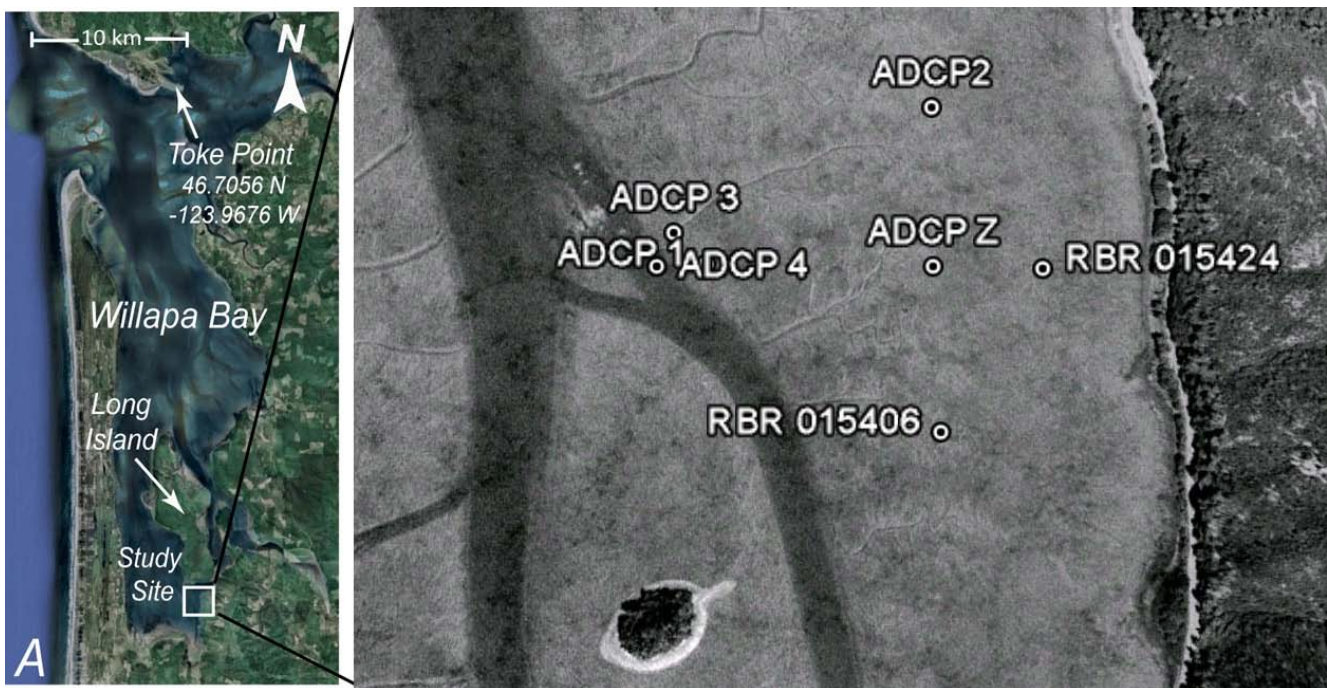


Figure 1. Willapa Bay study site. Five Nortek ADCPs were deployed on the tidal flat to determine wave climate and sediment redistribution during storms. Two RBR pressure transducers complemented the ADCPs measurements.

2.4 MUDEFLATS RIDGES AND RUNNELS

A field study carried out in Willapa Bay in July 2009 indicates that the mudflat is dissected by a series of gullies. Tidal gullies are elongated, small channels that run perpendicular to the main tidal channels along the direction of tidal velocity during high tide. Tidal gullies seem regularly spaced, with an average distance of 5m, and a depth of 20cm. We believe that these bedforms are caused by very

shallow flows on the mudflat platform and strongly depend on the mechanical properties of the substrate. To address this hypothesis we have measured tidal velocities in a tidal gully in Willapa Bay. To determine the relationship between tidal gully geometry and substrate characteristics we measured the critical shear stress both in the gully and on the platform with a Cohesive Strength Meter.

Modeling Component

3.1 MODELING THE DISTRIBUTION OF BOTTOM SHEAR STRESS IN TIDAL CHANNELS AND RUNNELS

We have developed a numerical model to compute the distribution of shear stresses inside a runnel as a function of tidal velocity and wave field. Several authors have already presented simplified methods to determine the distribution of shear stresses in channels as a function of flow velocity and energy slope. Pizzuto (1990) presented a model based on the modified area method of Lundgren and Jonsson (1964) to study bank erosion in a channel composed of noncohesive sediment (see also Parker 1978b and Ikeda et al. 1988). A similar approach was followed by Kovacs and Parker (1994), in which a Boussinesq eddy viscosity closure is applied to the stream-wise momentum equation. All these methods determine the velocity structure along a normal to the bed, and then aggregate the piecewise solution to compute the flow across the entire cross section and related bottom shear stresses. As a result these methods are applicable only when the bed curvature is small and the normals to the bed do not intersect, thus limiting the model utilization to very wide cross sections without abrupt changes in geometry. In this project we have developed a generalized method, named GCS3 (Generic Cross Section Shear Stress), which is able to determine the distribution of shear stress in channels cross sections of any shape (Fig. 2a). The model is outlined in Fagherazzi and Mariotti (2010)

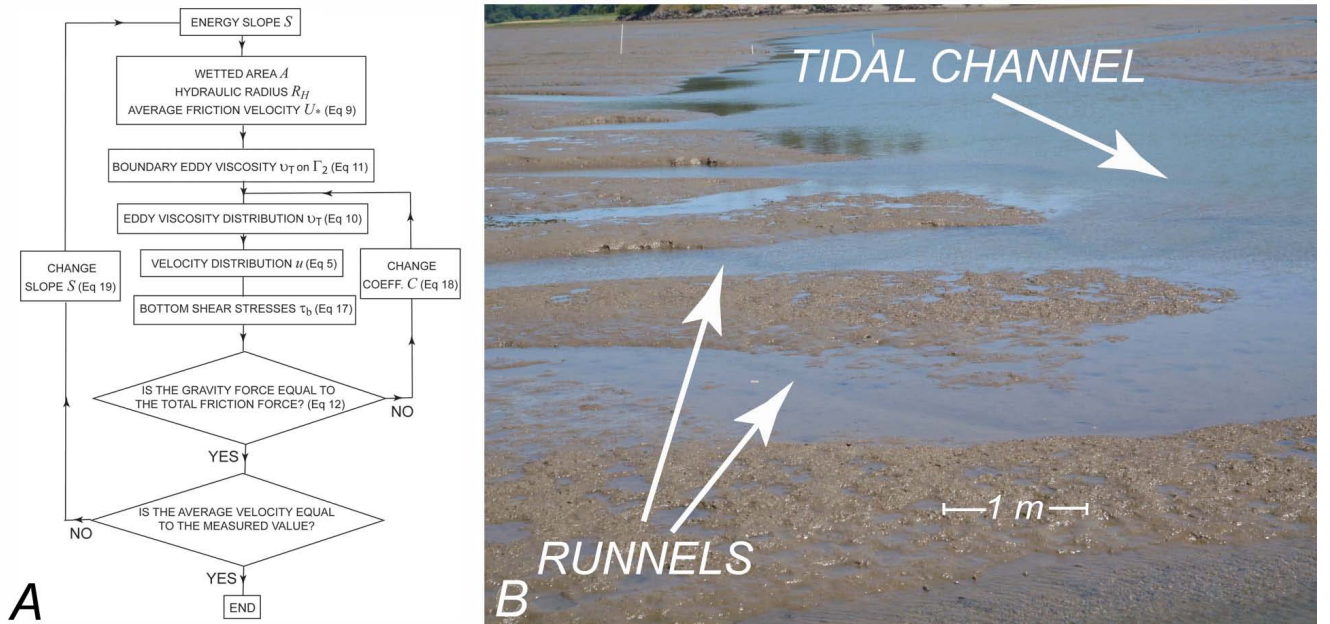


Figure 2. a) Flowchart of the GCS3 model for the computation of bottom shear stresses in a channel b) location of the studied runnels discharging in a tidal channel of Willapa Bay.

WORK COMPLETED

4.1 HYDRODYNAMICS OF TIDAL FLAT CHANNELS

We completed the analysis of the data collected in the 2009 deployment in Willapa Bay. Velocity profiles and water levels were simultaneously measured at different locations in a channel and on the mudflat for two weeks. The channelized flow was studied as a 1D open channel flow. From the continuity equation, a lateral inflow was predicted during ebb. Both advective acceleration and lateral discharge term, estimated directly from the velocity profiles, played a significant role in the momentum equation. Combining flow and SSC estimated using the ADCP backscatter, sediment fluxes were calculated.

4.2 WAVE CHARACTERISTICS IN MUDEFLATS

We retrieved all five ADCPs and the two RBR deployed in Winter 2010. We also started analyzing the data comparing them to wind data collected in Willapa Bay. Preliminary results show that wave characteristics during extreme events are well simulated by the wave model SWAN (Boij et al. 1999) but are not captured by standard analytical formulation of wave height as a function of fetch, water depth, and wind speed (Young and Verhaagen 1996).

4.3 MUDEFLAT RIDGE-RUNNEL SYSTEM

To study the processes acting in a mudflat ridge-runnel system we surveyed a cross section of a single runnel at high resolution recording the depth with 20cm spacing In April 2010. A Nortek Aquadopp Acoustic Doppler Current Profiler (ADCP) was positioned at the gully bottom flush with the bed and the sensors looking upward. The instrument was deployed from April 10 2010 to April 13 2010 (see Fig. 3).

One optical backscatter point sensor (OBS) was deployed at the runnel bottom oriented upward near the ADCP, a second OBS was deployed on the nearby ridge (same elevation of the tidal flat platform). The OBS were calibrated in the lab using mud collected at the location.

4.4 MODELING THE DISTRIBUTION OF BOTTOM SHEAR STRESS IN TIDAL CHANNELS AND RUNNELS

The GCS3 model was applied to the mudflat runnel surveyed in 2010, utilizing as forcing parameters measured velocities and water elevations (Fig. 3). During flood (instant 1 in Fig. 3) the water moves on the tidal flat platform toward the inner part of Willapa Bay. During the early phase of ebb (instant 2) the water moves in the opposite direction toward the inlet. During the late stage of the ebb (instant 3) the tidal channel becomes active and starts draining the tidal flat platform. The flow in the studied runnels reverses and flows southeast (negative sign in Fig.3). Once the water level is below the flat platform the flow is confined in the runnels reaching high velocities (instant 4). At this point all the remaining water on the tidal flat is drained through the runnels and then discharged in the network of tidal channels.

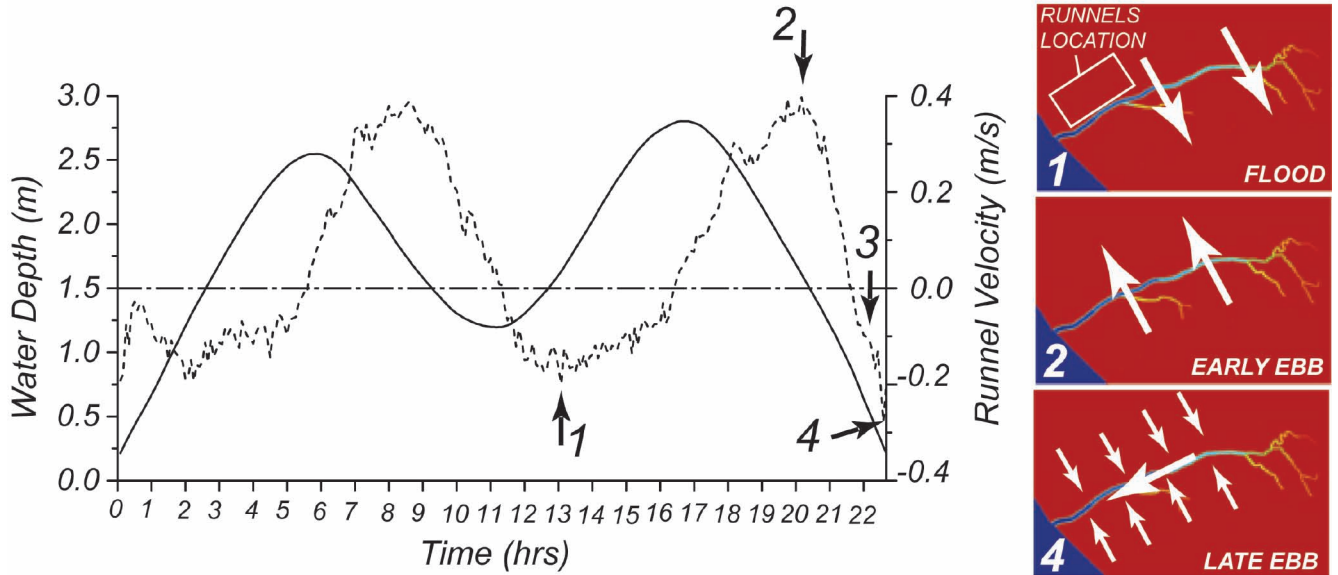


Figure 3. Average runnel velocity (dotted line) and water depth (solid line) from April 10 2010 at 10am to April 11 at 9am. The velocity is positive if directed toward South-East and negative if directed toward North-West. The cross section model for bottom shear stresses was applied at the instants 1 to 4. The flow direction on the tidal flat platform and its relationship with the nearby tidal channel is indicated for points 1,2 and 4 in the sketches on the right. Note how the velocity in the runnel reaches a value of -0.3 m/s at point 4, for a water depth of 0.26m, just before the ADCP emerges.

RESULTS

5.1 HYDRODYNAMICS OF A TIDAL FLAT CHANNEL IN WILLAPA BAY, WA

We were able to determine, from the continuity equation, a lateral flow discharging into the channel. This flow is present only during ebb, when the tidal flat drains the studied channel, and occurs for water levels between the tidal flat and 0.4 m below it. The advective acceleration and the lateral discharge terms play a significant role in the momentum equation during channelized flow. Therefore the channel hydrodynamics is inherently unsteady and cannot be described by a simple balance between gravity and friction, as it is commonly done in salt marsh creeks. The channel exports a large volume of sediments during ebb but import only a small fraction of it during flood (Fig. 4). Thus, the channel acts as sediment sink for the tidal flat in absence of waves. All the results have been presented in the manuscript Mariotti and Fagherazzi (2010).

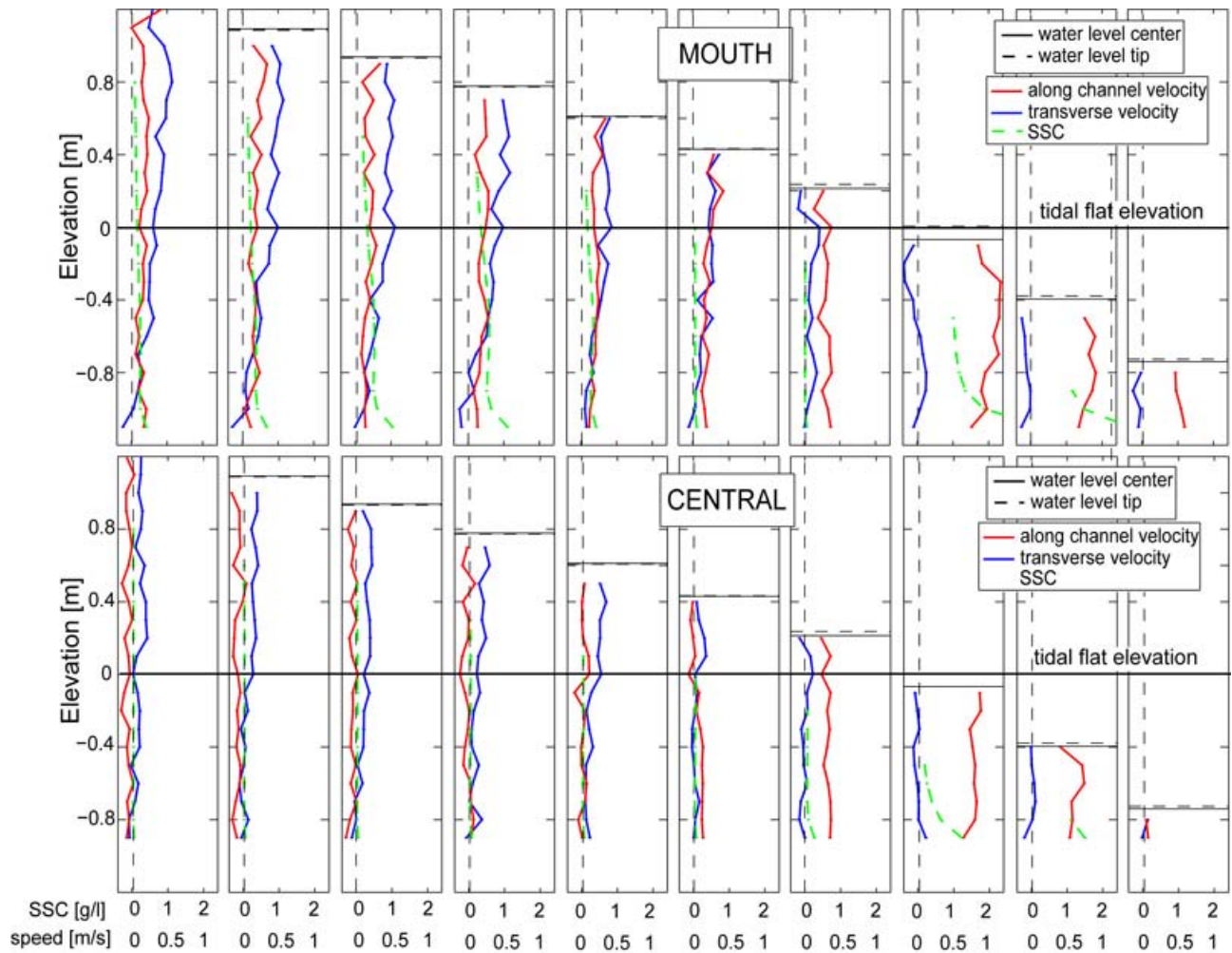


Figure 4 Velocity and suspended sediment profiles at the mouth and at the central cross section of the studied channel during ebb. The main speed is calculated in the direction parallel to the channel (250°N), lateral speed is calculated in the direction perpendicular to the channel (340°N).

5.2 MUDFLAT RIDGES AND RUNNELS

The runnels are hydraulically connected to the channels thus draining the platform during ebb. The velocity increases in the runnels, reaching values close to 0.3 m/s (Fig. 4). More importantly, flow confined in the runnels occurs for very shallow depths, producing elevated bottom shear stresses and sediment pulses in the runnels (Fig. 5). The computed bottom shear stress with the model GCS3 is of the order of 0.25 Pa, and therefore able to mobilize bottom sediments. Field evidence from shallower flows during flood indicates that the flow does not decrease for water depth around 5-10 cm, maintaining a value close to 0.3 m/s. These very shallow flows are clearly capable of keeping the runnels flushed and are responsible for the peak in sediment concentration measured in the nearby tidal channel during very low flow (Mariotti and Fagherazzi 2010). All the results regarding the hydrodynamics and sediment transport in the runnel-ridge system are presented in Fagherazzi and Mariotti (2010).

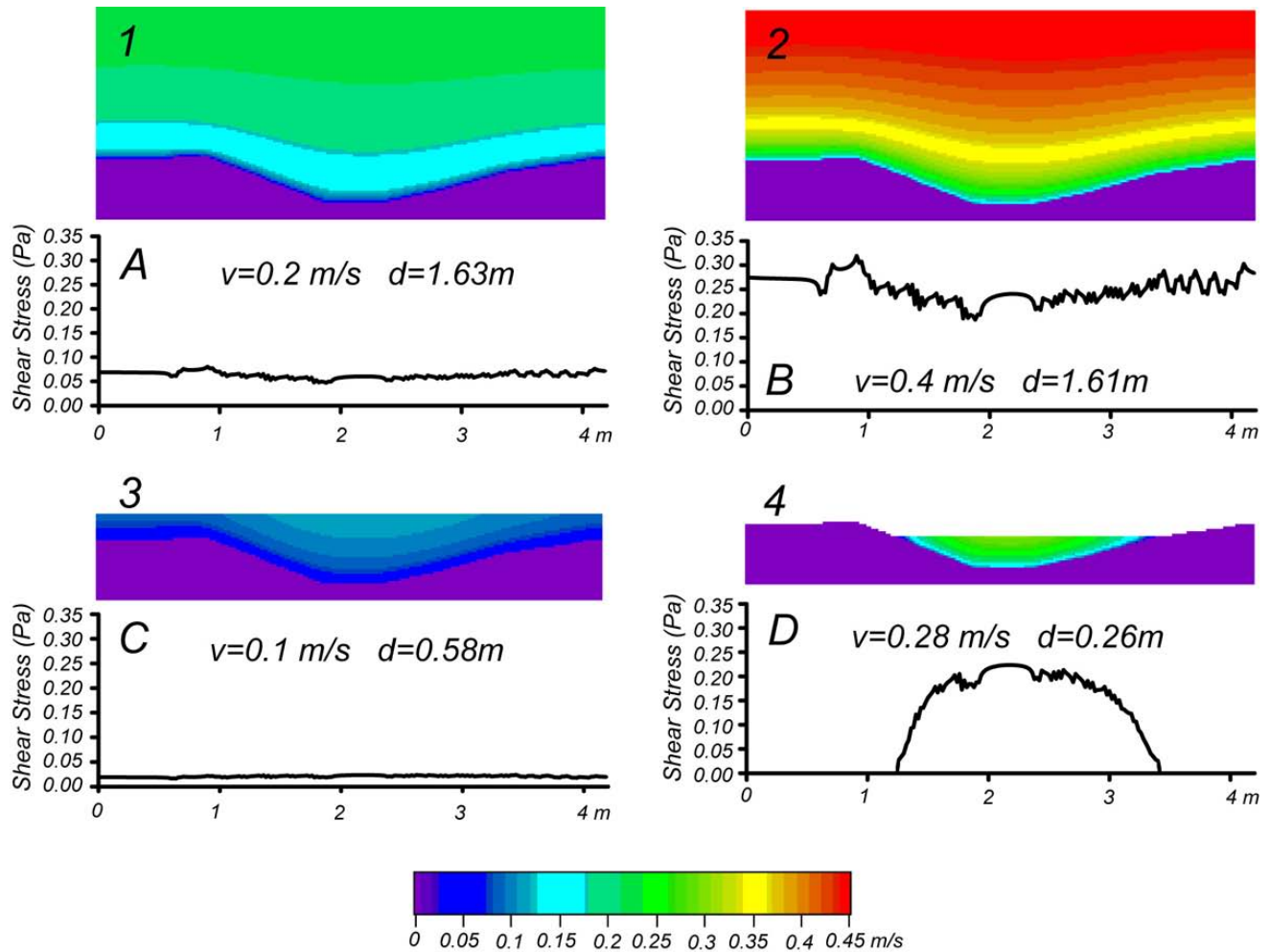


Figure 5 Distribution of velocity and shear stress in a mud flat runnel as a function of tidal elevation and discharge. The data refer to the four instant indicated in Fig. 3. The distribution of bottom shear stress and the water velocity in the cross section were computed with the numerical model GCS3. For very shallow flow the velocity in the runnels is high enough to produce sediment resuspension and maintain the runnel flushed.

5.3 INTERPLAY BETWEEN WAVES AND TIDAL CHANNEL HYDRODYNAMICS ALONG THE LOUISIANA COAST

An important result arises from the integration of the meteorological and sediment concentration data. Strong winds blowing from the south and southeast generate high waves and storm surges, and thus a large flux of sediments to the marsh during flood. However, the surge is often followed by an ebb phase with very high flow velocities, when the extra volume of water stored in the marsh is restituted to the ocean. Hence most of the sediments accumulated during the surge are remobilized during the following ebb, producing a limited net effect. On the contrary, strong winds from the mainland (from the north and northwest) trigger very low tides but not wave events at the shoreline. As a consequence, the net export of sediments facilitated by high ebb velocities is not compensated by an import of

sediments during the flood phase, since calm conditions at the shoreline do not favor sediment resuspension. Extreme low tides therefore seem favoring a net sediment loss through channel fluxes. Finally, moderate winds from the ocean can produce wave events that are decoupled from storm surges, thus avoiding fast ebb flows and sediment export during ebb. These events seem more favorable for sediment retention and marsh accretion (Fig. 6). The results of this research are reported in Fagherazzi and Priestas (2010).

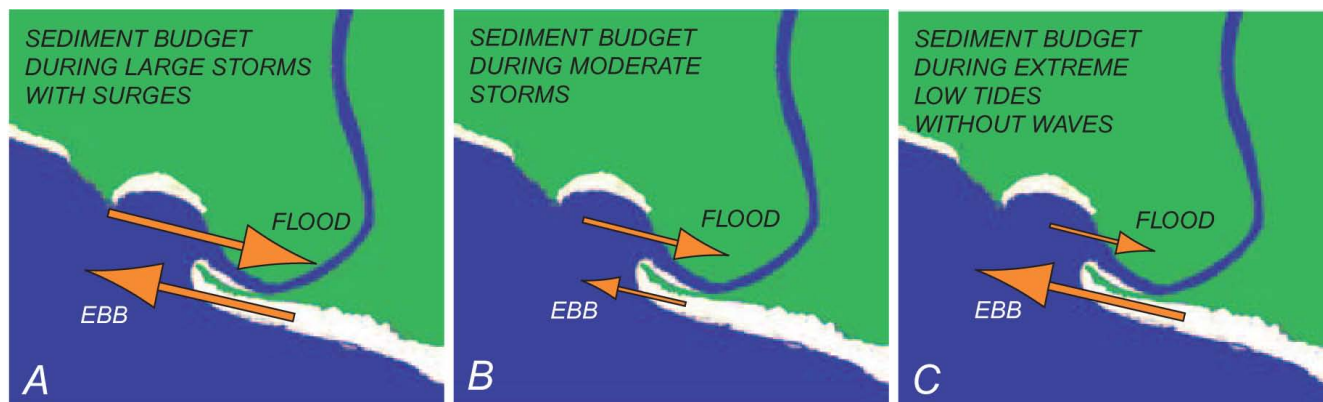


Figure 6 *Sediment fluxes under different meteorological conditions: (A) during storms triggering storm surges large volumes of sediments enter the channel but then exit during ebb tide; (B) moderate storms with waves yield to net sediment input to the salt marsh (the volume of sediments entering during flood is much larger than the volume of sediments exiting during ebb); (C) extreme low tides occurring when the wind blows from the mainland lead to sediment export during ebb that is not compensated by sediment input during the subsequent flood.*

5.4 WEVE-CUT GULLIES IN LOUISIANA MARSHES

We have discovered that the erosion of marsh boundaries by wave attack can be concentrated in selected locations giving rise to wave gullies. Wave gullies are triangular features that cut through the marsh scarp and extend in time both in length and width. They are usually equally-spaced and develop in cohesive, vegetated scarps. The convergent geometry of wave gullies concentrates the energy of incoming waves and creates a very strong swash with velocities higher than 1 m/s. The resulting flow hits with strength the gully head producing headwater erosion up to 20 cm/day under relatively common storm conditions along the Louisiana coastline (Fig. 7). The results of this research are reported in Priestas and Fagherazzi (2010)

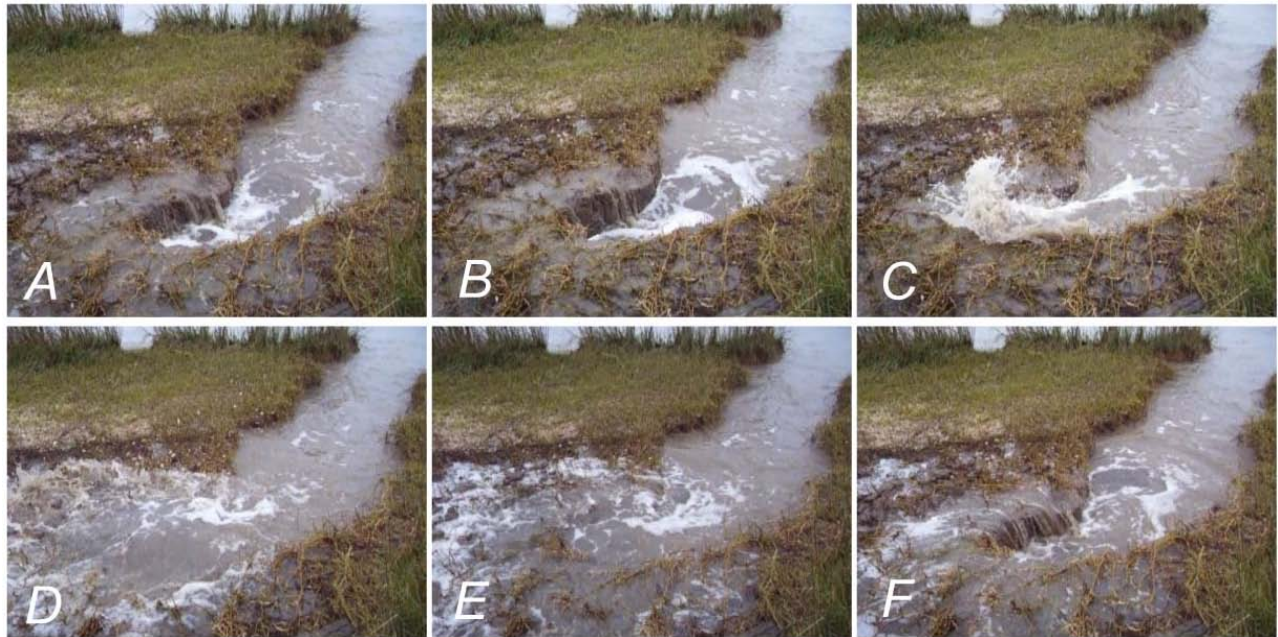


Figure 7 *Snapshots of a wave propagating in a wave gully: a) the wave is entering the gully; b) the wave propagates in the gully; c) the wave hits the gully head; d) water floods the marsh above the gully head; e) and f) the water returns in the gully*

IMPACT/APPLICATIONS

The collected data will help assessing the navigability of tidal channels in denied areas. Moreover, the characterization of wave climate along a muddy coast will provide useful information for navigation in very shallow water and landing. Our project will also establish the connection between the geotechnical properties of sediment substrates and the spatial and hydrodynamic characteristics of tidal channels. Finally, the feedbacks between tidal channels and waves will provide information on the origin of mudflat sediments and their characteristics.\

RELATED PROJECTS

The proposed research is designed to synergistically complement the already funded MURI project “Mechanisms of Fluid Mud Interactions under Waves” (<http://www.ce.jhu.edu/dalrymple/MURI/>). The MURI project studies the interactions between waves and muddy bottomsets in the shelf in front of the Rockefeller State Wildlife Reserve. In this project we will measure the sediment concentration in nearby tidal channels during the same period, and use this information to tune a model for tidal channel evolution.

Our instrument deployment in Willapa Bay is also fully complementary with ongoing research activities of the “Tidal Flats” DRI project. In particular, we will provide high resolution measurements of tidal and sediment fluxes in the channels dissecting the mud flats at the Willapa Bay DRI location.

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